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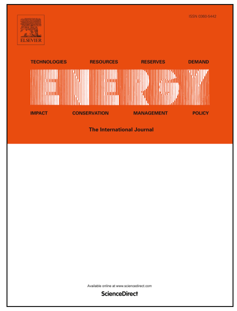


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# Effects of ambient temperature and trip characteristics on the energy consumption of an electric vehicle

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**Abstract**

This work evaluates the impacts of ambient temperature and trip characteristics on the energy consumption of an electric vehicle (EV) during road tests. The trip characteristics are here defined by the driving distance, stop time percentage and average vehicle speed. The analysis uses data collected from real-world driving of an EV in one of the most populous metropolitan regions in the UK for almost four years, using a dedicated monitoring software for real-time vehicle data processing. The results reveal that the EV specific energy consumption (SEC) increases under operation at low temperature, also showing a larger scatter. Significant changes in SEC are linked to auxiliary energy demand and trip characteristics, especially under cold temperatures. Trips complying with a real-world driving test procedure produced lower SEC than random trips at cold temperatures but showed closed values at moderate temperatures. At both cold and moderate temperature conditions the EV presented lower SEC for urban driving, in comparison with rural and motorway operation, confirming its adequacy for application in metropolitan areas. Urban EV operation at low temperatures from 0°C to 15°C has a trip range 28% lower than driving at moderate temperatures from 15°C to 25°C.



Keywords: Electric vehicles; energy consumption; ambient temperature; heat load; real-world conditions.

## 1. Introduction

The transportation sector receives increased attention from governments worldwide, as it is largely responsible for global environmental pollution, greenhouse gas emissions and energy consumption [1]. The environmental and energy concerns have promoted the widespread development of electric vehicles (EVs) [2]. The environmental benefits provided by EVs are directly related to their energy consumption, which is mainly estimated using current legislative driving cycles [3]. The differences between real-world driving conditions and standard test schedules at controlled laboratory conditions result in significant variations of energy consumption, emissions and range [4]. For this reason, the development of real-world driving cycles for specific regions can provide more representative results from both experiments and simulation [5]. Furthermore, the discrepancy of EV energy consumption measured under real-world driving and the one obtained from laboratory testing can eventually be much higher compared with internal combustion engine (ICE) vehicles. This is especially due to the added load from the auxiliary systems on EV battery.

Variations on EV parameters such as vehicle weight, speed and load from the auxiliaries may have a substantial impact on the EV driving range compared to ICE vehicles because the energy storage of the latter, the fuel tank, is larger and denser [6]. Therefore, the measured energy consumption values provided by car manufacturers can overestimate the actual range of EVs since their testing are carried out under ideal conditions with minimum load. The provision of accurate data of EV energy consumption and range, and identification of related affecting factors are essential to remove customers' anxieties and help to widespread the EV market [7].

Different aspects influence the energy consumption of EVs, including traffic conditions, which affect vehicle speed and acceleration, infrastructure, such as road gradient, environmental conditions, such ambient temperature, and driving behaviour [8]. Two factors affect the driving behaviour of EVs: regenerative braking, which can change the driver style to improve the amount of recovered energy, and powertrain configuration, which performance and noise characteristics give different perceptions to the driver [9]. The environmental conditions have a substantial impact on EV energy consumption, particularly the ambient temperature, which lacks adequate research data to evaluate its impact on the overall EV energy efficiency [10].

The ambient temperature was reported to affect the energy consumption of both EVs and ICE vehicles similarly, as during colder weather the increase in air density lead to increase in rolling resistance and air drag [11]. In addition, at low temperatures both electric motor and engine lubricants operate outside their optimal range, which translates into decrease of overall driveline efficiency. A rise in the energy consumption of EVs has been observed due to the use of auxiliary devices to keep the occupants at a comfort level with the use of air conditioning at high temperature weather and heater at cold weather conditions [12]. The thermal energy from the electric motor in EVs is unable to provide the heating requirement during winter, which notably affects the range due to increase in energy consumption [13].

The ambient temperature outside influences the amount of recovered energy during regenerative braking and affects battery efficiency [14]. If the interactive effects between the ambient temperature and the auxiliary load are ignored, it will lead to overestimated energy consumption of the heater in warm weather and underestimated air conditioning in cold weather. Using operation data of heating and cooling systems from different cities in China, laboratory tests of several EV models with different battery types showed that energy consumption increased by 20% and 67% at the ambient temperatures of 30°C and -7°C, respectively, compared with moderate temperatures [15]. The tests also revealed that differences in consumption between vehicle models are caused by the heating and cooling system, and for different battery types the differences were due to charging and discharging performance at low temperature.

The variation in energy consumption of EVs across different seasons and weather conditions has been shown using real-world data of 12 months for several driving application [16]. The results pointed out a significant reduction in driving range during cold weather to 64% of expected from the standardised driving cycle. However, the reason for the variation in energy efficiency could not be determined due to the lack of data when the auxiliary systems were used. The relationship between the ambient conditions and driving range using a drive-to-depletion method that involves measuring the covered range by driving the vehicle from the fully charged battery until depleted using battery state-of-charge (SOC) reading has been examined [17]. The results show a linear correlation between the ambient temperature outside and the EV range, however, the determination of energy consumption was not accurate as the vehicle parameters were extracted at extremely low frequency.

The effects of temperature on EV energy consumption have also been studied using computer simulation modelling. A simulation model developed to measure the influence of wide temperature range on EV energy consumption under a legislative driving cycle showed a significant reduction in driving range at cold temperatures, compared with optimal temperatures where the auxiliary demand was at a minimum [18]. Due to changes in atmospheric conditions, the EV driving range varies from 25% to 35% between northern and southern European countries [18]. The climate data of three major cities in the United States was used in a simulation tool to reveal that the utilisation of heating, ventilation and air conditioning (HVAC) system increases EV energy consumption by 9%, 12% and 24% in hot, moderate and cold climates, respectively [19]. A combination of microscopic traffic and energy prediction models showed that, if the ambient temperature drops by 12°C, energy consumption increases by 11% at motorway driving speed of 130 km/h and peaks with an increase of 55% at residential driving speed of 30 km/h [20].

Using long-term GPS data collecting every 60 s for driving EVs in Japan, the influence of road gradient on EV energy consumption was explored [21]. Other various factors were considered in the study including trip distance, average speed and air conditioning or heater usage. The trips using heating and air conditioning systems presented average specific energy consumption (SEC) twice as larger as the other trips. From the evaluation of data collected in Shanghai, China, changes in trip distance, average speed and temperature have shown a direct impact on EV energy consumption while battery initial SOC had no significant impact on EV efficiency [22].

The objective of this work is to investigate the energy consumption of an EV under different driving and ambient conditions, based on data collected from real-world driving in West Midlands roads, in the UK. The relation between ambient temperature outside the EV with trip characteristics - distance, stop percentage and average speed - and their impacts on energy consumption are the main research gaps here addressed. The monthly variation of energy consumption and expected driving range during different conditions and seasons are also here evaluated. The main novelties of this paper are:

- The effects of year-round ambient temperature on total EV energy consumption and auxiliary system energy consumption are unveiled for various trip characteristics.
- Unprecedented data of EV energy consumption from trips meeting a representative real-world driving cycle (RDC), the European Real Driving Emissions test procedure (RDE), compared with results from random driving provides novel information for further RDC/RDE test standard development.

The outcomes of this research provide real-world data on key factors to accurately predict EV driving range and identify potential solutions to reduce energy consumption under different ambient temperature and driving conditions. The paper contribution can be further highlighted, as real-world energy consumption is a major performance indicator for EV drivers, manufacturers and legislators due to its important role on energy efficiency, environmental impacts and economic benefits in transportation system [23]. The next sections describe the methodology applied, results and discussion, and the main conclusions achieved.

## 2. Methodology

The dataset in this research was obtained from random road operation of a Nissan Leaf EV model equipped with a 24 kWh battery. While the study is based on a single vehicle the analysis is applicable to other EVs in the UK market of close specifications (Table 1), such as BMW i3 and Renault Zoe. This model is classified as a compact vehicle, which segment has the largest market share in the UK of 60% [24]. The driving was conducted in the city of Birmingham, the second largest city in the UK, during the period from January 2016 until September 2019. The data was collected at a frequency of 1 Hz from the controller area network (CAN) bus by a data logger connected to the vehicle on-board diagnostics (OBD) port. The data logger synchronised the data in real-time and stored it in the cloud, making it accessible by a dedicated ViriCiti monitoring software. The main vehicle parameters used in this study were ambient temperature (°C), trip time step (s), vehicle speed (km/h), battery current (A) and battery voltage (V). These readings were extracted from the vehicle sensors.

The data exported from the monitoring software was processed and filtered using MATLAB software. For every trip, the distance and duration were calculated using the recorded time interval and vehicle speed. The analysis excluded any trip shorter than 1 km or taking less than 5 minutes. A total of 1,137 trips were evaluated under varying driving conditions across different ambient temperatures outside, ranging from 0°C to 33°C, trip duration taking from 5 min to 1 h 28 min, and travel distance from 1 km to 75.8 km. Different drivers carried out the driving under various driving conditions during different times of the day independent from changes in weather conditions. No specific route was selected to ensure that various road types were covered, and the driver had no restriction to use any of the vehicle auxiliaries in order to obtain a realistic representation of the driving characteristics in the UK. Around 65% of the trips started with a battery SOC of 70% or higher. The elevation difference between the start and end of each trip was below 100 m for nearly all trips due to the flat nature of the area, limiting the impact of road grade on the overall vehicle energy consumption. Therefore, the relationship between ambient temperature and road grade impacting the variation in SEC is not considered in this work.

Using the readings of battery voltage, V (V), and current, I (A), the power consumed from the battery, P (kW), was calculated at every measured time step dt (s) along the trip duration t (s), and used to draw the power consumption curve for every trip. The area integration of the power consumed with the time step gives the total energy consumed during the trip, $E_{tot}$ (kWh). Using the energy consumed during the trip and the travel distance, s (km), the SEC (kWh/km) is calculated as follows:

$$SEC = \frac{E_{tot}}{s} = \frac{\int_0^t VIdt}{s} \cdot \frac{10^{-3}}{3600} \quad (1)$$

The maximum EV driving range, $s_{max}$ (km), is the total distance the vehicle can cover with a single charge from fully charged battery until depletion state, and is so calculated based on the measured SEC:

$$s_{max} = \frac{C_{battery}}{SEC} \quad (2)$$

Where $C_{battery}$ is the usable battery capacity observed when it is fully charged (kWh).

The battery usable capacity is restricted by the battery management system (BMS) to protect it from overcharging and discharging events and avoid situations that can compromise the battery pack by reducing its life cycle or leading it to catch fire [25]. To ensure no permanent damage occurs to the battery and avoid deep discharging, the rated capacity cannot be fully accessed or used [6]. Following recommendation from previous authors [26], the usable battery capacity is here adopted as 87.5% of the nominal rated capacity.

The total energy consumed $E_{tot}$ includes the tractive energy required to drive the vehicle, $E_{tra}$ (kWh), the energy needed to operate the auxiliary devices in the vehicle, $E_{aux}$ (kWh), and the total energy losses due to braking, aerodynamic drag, rolling road resistance, friction of the moving components, and electric losses, $E_{loss}$ (kWh). The tractive energy can be split into two parts: one is the energy required by the drivetrain, $E_{drv}$ (kWh), and the other with opposite sign is the recovered energy during regenerative braking, $E_{reg}$ (kWh). Therefore, the sum of these energies gives the total consumed energy written as:

$$E_{tot} = E_{tra} + E_{aux} + E_{loss} = \left(E_{drv} - E_{reg}\right) + E_{aux} + E_{loss} = E_{cons} - E_{reg} \qquad (3)$$

where $E_{cons}$ (kWh) is the net consumed energy by drivetrain, losses and auxiliary system:

$$E_{cons} = E_{drv} + E_{aux} + E_{loss} \qquad (4)$$

The effect of temperature on battery performance is not within the scope of this paper, but it has been reported that a decrease in temperature increases the battery internal resistance and, therefore, decreases the amount of energy that can be extracted from the battery [27]. On the other hand, high temperatures do not affect battery charging and discharging performance but may cause a rapid increase in battery degradation and self-discharging [28].

The battery is expected to lose between 2% to 5% of its rated capacity in two years if the user drives the vehicle for 45 km/day [29]. In the current study, the EV had an initial odometer reading of 4031 km in January 2016 and, at end of testing in September 2019, the reading was around 19225 km, corresponding to about 11 km/day. Therefore, battery degradation during the test period is here assumed to be negligible as the travel distance per day was very low. Likewise, the ageing of other vehicle components was not considered due to its minimal impact. For instance, the electric motor of an EV is likely to operate over 20,000 h or 15 years without degrading power delivery or efficiency [30]. This lifespan is much above that of conventional vehicles, which ranges between 6,000 h and 8,000 h [31].

A method to determine the auxiliary power consumption during vehicle operation was developed, as the data logging device used to collect data was unable to record the status of the HVAC system in separate from the total power consumption. Figure 1 shows the vehicle speed and the total power consumption of a recorded trip randomly selected to illustrate the method applied to determine auxiliary power for all scheduled or unscheduled trips. The power consumed in the periods when the vehicle speed is zero is attributed to the auxiliary systems, following a similar assumption adopted by other authors [32]. When the vehicle is moving, there is still power consumption from the auxiliary system but it cannot be directly extracted from the data, as observed between sections 1 and 2 in the figure. The auxiliary power is estimated using data interpolation between the last observed total power value before the vehicle starts to move and the value when the vehicle stops. This corresponds to the time range from 15 s to 81 s in the figure. The subtraction of the auxiliary power curve from the total power curve originates a new curve which positive part is the sum of drivetrain and losses power consumed from the battery, while the negative part is the regenerative power recouping back into the battery. The area integration of the power curves of auxiliaries, drivetrain and losses provides the energy consumed by each component, while the regenerated energy is given by the absolute value of the integration of the regenerative power curve.

The determination of SEC from road driving could be more easily comparable if all trips considered had similar characteristics; however, in real vehicle utilisation, a wide variety of trip lengths, stops and driving conditions are encountered. One major issue of using random trips is that it gives short trips the same weight as medium or long-distance trips on impacting the average SEC calculation, leading to widely scattered results. As a consequence, one may still lean to the use of standard driving cycles for comparison purposes. In order to allow future correlations, results were also built from selected trips attending the specifications and boundary conditions of the RDE test procedure, a real driving cycle adopted by the European Union (EU) [33].

In agreement with the RDE regulation, the datasets in every trip were divided into three sections based on vehicle speeds: below or equal to 60 km/h (urban), between 60 km/h and 90 km/h (rural), and above 90 km/h, with a minimum of 5 min at 100 km/h or higher speed (motorway) [34]. High auxiliary power demand at the start of the trip has less impact on the EV specific energy consumption in long trips, which, thus, tend to produce better estimates of actual energy consumption than short trips. Also attending the RDE requirements, only trip sections with distance longer than 16 km were selected. The RDE test procedure also requires 15 km/h to 40 km/h for the urban average vehicle speed and 6% to 30% stop percentage of trip time in urban operation [34]. The trips are further filtered using dynamic boundary conditions specified in the second RDE package [35] to reduce the differences in driving characteristics between the sections of each operation mode. These conditions are based on vehicle speed and acceleration to limit the impact of too smooth or too aggressive driving on SEC. The requirements of the RDE schedule used in this study are summarised in Table 2.



## 3. Results and Discussion

Figure 2 shows the changes in SEC and ambient temperature based on a monthly average and across different seasons. The lowest SEC values are obtained between June and July, when the ambient temperature reaches its peak. For the other months, as the temperature drops, the SEC is increased. The highest energy consumption is recorded between December and January. The increase in energy consumption from the lowest average values at summer months to the highest average values in the cold months is of 69.5%.

Figure 3 shows the SEC and the average ambient temperature for each trip. It can be noticed that data dispersion is higher at lower temperatures. The relationship between the ambient temperature and the SEC has a non-linear u-shape trend, with the dashed line representing the best fit to the data average, in agreement with previous observation by other authors [7]. In general, it is observed decreasing SEC with increased temperature from cold weather condition until reaching minimum at around 21°C. Similar findings are reported by other authors Qi, Yang [22], who also found that the energy consumption decreases with an increase in temperature. With further increase of ambient temperature, the SEC rises again. The temperature where the lowest energy consumption was here achieved is close to the range found elsewhere Liu, Wang [14], between 21.8°C and 25.2°C.

Similar to conventional ICE vehicles, EVs have several auxiliary devices to improve the driver experience and comfort. In EVs, three sources are attributed to the total energy consumed by the auxiliaries. Firstly, the HVAC system to keep the occupants at comfort levels. Secondly, the battery thermal management (BTM) system, whose purpose is to maintain the optimal battery operating condition [36]. Lastly, other auxiliary devices such as lighting, entertainment system, navigation system and any other optional comfort systems. These other auxiliary devices have a relatively low impact on power consumption [37], accounting for just around 50-70 W, and, thus, can be neglected [38].

The battery pack in the EV here utilised is sealed, and the BTM can be classified as a passive air-cooled system, as it depends directly on the natural airflow around the pack [39]. Therefore, the ambient temperature can be used to represent the battery temperature. The vehicle contains an electrical battery heater that turns on at -17°C to heat the battery and switches off at -10°C [40]. As the ambient temperature during the data collecting period did not reach these extreme cold conditions, no power was consumed from the battery heater. Therefore, the energy consumed by the auxiliaries is primarily attributed to the HVAC system.

Figure 4 shows the variation of the energy consumed by the auxiliaries with changing ambient temperature outside. The auxiliary SEC reaches a minimum at around 18°C, increasing for trips outside the moderate temperature range. A higher variation in the auxiliary SEC is observed at temperatures below 10°C, compared to the rise at warmer conditions. The higher impact of heating systems among EV auxiliary devices was also reported by other authors [41]. Higher energy consumption at low temperatures outside is attributed to air warming inside the vehicle for cabin comfort or window defrosting [12]. Therefore, the larger spread noticed when more heating is required depends on several factors but also reflects the driver reaction to reach a temperature inside that provides the desired comfort level. For similar ambient temperature outside, the thermal sensation to the driver may change from different trips and affects his heating demand. The high spread of the auxiliary SEC data at low temperatures affects the span of the EV specific energy consumption in the same range (Fig. 3).

The crucial data obtained from the CAN bus to calculate vehicle and auxiliary power consumption and SEC (Eqs. (1) to (4)) are battery voltage and current, and vehicle speed (time and distance), together with ambient temperature as the main independent variable in this evaluation. A sensitivity analysis of the battery parameters has been carried out through the variation of SEC with ambient temperature, as shown by Fig. 5. The accuracies of battery voltage and electric current measurements are $\delta V = \pm 0.01$ V and $\delta I = \pm 1$ A. The sensitivity of vehicle and auxiliary SEC to the measured battery voltage is negligible, therefore it is not represented in the figure. The sensitivity of vehicle and auxiliary SEC to battery current measurements varies from 0.02 kW.h/km to 0.03 kW.h/km and from 0.01 kW.h/km to 0.02 kW.h/km, respectively, in the whole range of ambient temperature investigated.

The rise of energy consumption when the vehicle operates outside moderate temperatures about 21°C, under colder or hotter weather conditions, can be directly linked to the added consumed energy used to run the auxiliary devices. Figure 6 shows the relationship between the energy consumption of the auxiliary systems and the vehicle SEC. Despite the scattered data, a highly linear correlation is obtained as indicated by the calculated Pearson correlation coefficient of 0.87. This behaviour of increased SEC with increasing load from the auxiliary systems is due to the energy used to run auxiliary devices being drawn from the EV battery. Therefore, any rise in power required from the auxiliaries leads to a direct impact on the EV specific energy consumption.

Figure 7 presents the ratios of the consumed energy by the auxiliary devices ($E_{aux}$) and the recovered energy from the regenerative braking system ($E_{reg}$) to the net consumed energy by the EV ($E_{cons}$). At moderate conditions, with temperatures between 14°C and 22°C, the energy consumed by the auxiliaries accounts for less than 10% of the net EV energy consumption. However, at extreme conditions, with temperatures below 4°C or above 32°C, the energy drawn by the auxiliaries reaches 25% and up to 38% of the net consumed energy by the EV. The difference in energy consumption between cold, moderate and warm conditions is also affected by the changes in regenerative braking efficiency. According to the literature, the capability to charge the battery is affected by driving behaviour or drop in battery performance with ambient temperature changes. The exact portion of these factors that affect regenerative braking efficiency is suggested as a subject of future research. The recovered energy by the regenerative braking system reaches highs of 30% to 32% of the net consumed energy at temperatures between 15°C and 30°C. At the lowest temperature in the range studied, of 0°C, a minimum energy recovery of 14% of the net consumed energy is achieved.

Trip characteristics have significant impact on EV specific energy consumption. Figure 8 shows the typical profile of auxiliary power consumption of a random trip taken in a fairly flat road with the outside temperature at 5°C, recorded in the first 1600 s after start. The figure also includes the vehicle speed, trip distance and inside temperature profiles. The auxiliary power peaks soon after the start of the trip and it stays high until about 3 km, when it drops to about half of the peak value. This behaviour is because the heating system operates at maximum power at the start of the trip to reach the desired temperature as quickly as possible, thus requiring extra power. With an increase in distance the auxiliary power tapers to lower values, as the inside temperature reaches comfortable levels for the driver and heating requirements are reduced. This illustrates how cold weather and short trips are critical conditions to increase auxiliary power consumption, leading to high scattering in the SEC (see Fig. 4).

Another parameter that can significantly impact the EV energy consumption is the stop percentage of the trip time, which must be separated from the temperature effects. Figure 9 highlights different stops for a 6-min section of a typical trip profile occurred during cold conditions in urban driving, at 3°C. The results reveal that during the stops, when the EV normally has zero tractive power values, there is still power consumption from the use of auxiliaries. Therefore, with increased number of stops an increase in SEC is expected. The longer the percentage of stop time in a trip, the higher the SEC, as the cumulative auxiliary energy consumption is increased. The impact of stops is due to high auxiliary power demand at the start of the trip, as mentioned previously. At the start of the trip and before the vehicle starts to move there is high auxiliary power consumption, which is amplified during winter due to the use of heating systems such as windows defrost [42]. Therefore, an increase in the stop time percentage directly translates into a rise of the SEC. The combination of long stop time and colder temperatures has the largest impact on increasing the SEC, as demonstrated by Fig. 10.

A comparison of the average values of EV SEC and the auxiliary SEC between all random trips and the combination of the selected sections that met the RDE criteria is presented by Fig. 11. At cold temperatures, the SEC of the RDE-compliant sections is significantly lower than the SEC of data, dropping about 30% at 1°C. This is mainly due to the removal of the short-distance (< 16 km) and large stop percentage (> 30%) trips from the RDE selected ones, as those types of trips present higher energy consumption by the auxiliaries. This can be also observed from the similar drop of SEC presented by the auxiliaries at colder temperatures, when comparing the RDE-compliant sections against all trips. At moderate temperatures, from around 17°C to 22°C, the SEC of all trips had similar values as the SEC of the RDE-compliant ones. In this temperature range, the auxiliary SEC reaches minimum values, being slightly lower for the RDE-compliant trips in comparison with all trips.

Figure 12 shows a breakdown of specific energy consumption and regeneration for the RDE sections under urban, rural and motorway operation in the temperature ranges from 0°C to 15°C and 15°C to 25°C. In general, the energy required for drivetrain operation plus losses are from 14% to 27% higher in the low temperature range for all RDE operation modes. The stop-go situations in urban driving that are normally followed by acceleration events require extra power to move the vehicle from standing still, being the reason for the higher energy consumption by the drivetrain and losses at these operating conditions. Furthermore, the efficiency of electric motors is decreased under low speed and power operation, thus increasing energy consumption in urban driving [43]. For rural and motorway operation the vehicle travels at higher speeds, with higher air resistance decreasing its efficiency [32] as more power is needed to overcome the aerodynamic drag, thus increasing the specific energy consumption. The energy required by the auxiliaries is more than twice higher in the low temperature range under urban operation, keeping similar levels for the two temperature ranges under rural and motorway operation modes.

While the drivetrain energy consumption plus losses are close for urban and motorway operation at both temperature ranges, the total EV energy consumption is from 20% to 32% lower in urban driving in comparison with motorway driving (Fig. 12). This is because energy regeneration is 6 to 14 times higher during urban driving, even with 2 to 5 times higher energy demand by the auxiliaries. The relatively small energy regeneration for both rural and motorway operation denotes that regenerative braking is less actuated in these driving modes, which present more cruising speeds, in comparison with urban driving. In contrast, frequent deceleration events and repeated stops in urban driving make the most of regenerative braking. These results show that EVs operate more efficiently under urban and rural conditions than in motorways, backing the initiatives to promote a rapid deployment of EVs in largely populated zones.

Considering that the EV model used in this investigation has an average SEC of 0.15 kWh/km for the combined RDE sections (Fig. 12), the real-world driving range of the EV calculated using Eq. (4) is 140 km. This is about 30% lower than the official range published by the manufacturer based on the New European Driving Cycle (NEDC) in laboratory testing, of 199 km [6]. If the vehicle is primarily used in urban trips, and considering the calculated average SEC of 0.11 kWh/km at moderate temperatures from 15°C to 25°C (Fig. 12), it will attain maximum range of 193 km. This reveals a drop of 28% in range for urban operation in the cold temperature range, from 0°C to 15°C, which has the same SEC as the overall RDE section. Following similar analysis for motorway operation, the range will drop 14% from 130 km to 112 km under moderate and cold temperatures, respectively.

Figure 13 shows the relationship between SEC and average vehicle speed at the temperature ranges of 0°C to 15°C and 15°C to 25°C in urban, rural and motorway operation of RDE sections (Tab. 2). In general, the energy consumption is higher in the lower temperature range regardless of the average speed. In the temperature range from 15°C to 25°C a minimum SEC is achieved at an average speed of 45 km/h and, in the range from 0°C to 15°C, the minimum SEC occurs at 55km/h, both under urban operation. The prominent SEC increase at lower speeds in the low temperature range has the energy consumed by the auxiliary systems as the dominant factor. Also, trips with low average vehicle speed have large stop time percentage, as discussed previously, leading to high SEC. Similar behaviour of SEC variation with vehicle speed was found by other authors [7], where the maximum efficiency occurs at a driving range between 45 km/h and 56 km/h. In the domain of rural and motorway operation, the SEC increases with increasing average vehicle speed in both low and moderate temperature ranges.

## 4. Conclusions

From the results obtained in this investigation and the performed evaluation, the following conclusions can be drawn:

- Decreasing ambient temperature outside leads to increased EV energy consumption, with larger variability during cold conditions.
- Changes in auxiliary energy consumption with ambient temperature are largely related to the use of HVAC system, as there is no evidence the other auxiliaries have a significant impact. Short-distance trips combined with high stop time percentage and low ambient temperatures produce the most favourable condition to increase SEC, as the HVAC system is more required.
- The regenerative braking system shows lower efficiency at low ambient temperatures. According to the literature, this is probably due to the decreased battery charging capability at these conditions.
- Trips that comply with the RDE test procedure produce lower SEC than the random trips in the cold temperature range from 0°C to 15°C, as a result of the higher impact of auxiliary heating energy requirement in the non RDE-compliant short trips. In the moderate temperature range, from 15°C to 25°C, the RDE trips produce close SEC values to random trips.
- Urban and rural driving complying with the RDE procedure produce near SEC results in both cold and moderate temperature ranges, with motorway operation always producing higher SEC. Urban driving requires more energy to the auxiliary system, but also regenerates larger amounts of energy than rural and motorway driving.
- The vehicle range calculated from the combined RDE sections is about 30% lower than the value declared by the manufacturer from laboratory tests following the NEDC standard.

Urban EV driving at cold conditions has a range 28% lower than operation under moderate temperatures.

- The EV energy consumption is minimum at the average speed of 55 km/h under cold conditions from 0°C to 15°C, and, for moderate temperatures from 15°C to 25°C, the lowest SEC value is obtained at 45 km/h. This reveals the EV operates more efficiently in the urban region, supporting the efforts for its deployment in metropolitan areas.

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**List of symbols**

| | |
|---|---|
| $C_{battery}$ | Usable battery capacity when fully charged (kWh) |
| $E_{aux}$ | Energy required to operate the auxiliary devices (kWh) |
| $E_{cons}$ | Net consumed energy by drivetrain, losses and auxiliary devices (kWh) |
| $E_{drv}$ | Energy required by the drivetrain (kWh) |
| $E_{loss}$ | Total energy losses due to braking, aerodynamic drag, rolling road resistance, friction of the moving components, and electric losses (kWh) |
| $E_{reg}$ | Energy recovered during regenerative braking (kWh) |
| $E_{tot}$ | Total energy (kWh) |
| $E_{tra}$ | Tractive energy (kWh) |
| I | Battery current (A) |
| P | Battery power (W) |
| s | Travel distance (km) |
| $s_{max}$ | Maximum EV driving range (km) |
| SEC | Specific energy consumption (kWh/km) |
| t | Time step (s) |
| V | Battery voltage (V) |

**List of abbreviations**

| | |
|---|---|
| BMS | Batter Management System |
| BTM | Battery Thermal Management |
| CAN | Controller area Network |
| EV | Electric Vehicle |

| | |
|---|---|
| HVAC | Heating, Ventilation and Air Conditioning |
| ICE | Internal Combustion Engine |
| NEDC | New European Driving Cycle |
| OBD | On-Board Diagnosis |
| RDE | Real Driving Emissions |
| SOC | State of Charge |
| UK | United Kingdom |

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Table 1. Summary of the main vehicle specifications.

| PARAMETER | TYPE OR VALUE |
|---|---|
| Car model | Nissan Leaf |
| Vehicle class | C-Segment (compact vehicle) |
| Battery capacity | 24 kWh |
| Battery chemistry | Li-ion |
| Maximum motor power | 80 kW |
| Vehicle mass (curb weight/gross weight) | 1521/1761 kg |

Table 2. Summary of RDE requirements.

| TRIP CHARACTERISTICS | | BOUNDARIES |
|---|---|---|
| Vehicle speed range | Urban | ≤ 60 km/h |
| | Rural | > 60 km/h and ≤ 90 km/h |
| | Motorway | > 90 km/h |
| Average vehicle speed | | 15 km/h to 40 km/h for urban driving |
| Stop percentage | | 6% to 30% of urban time |

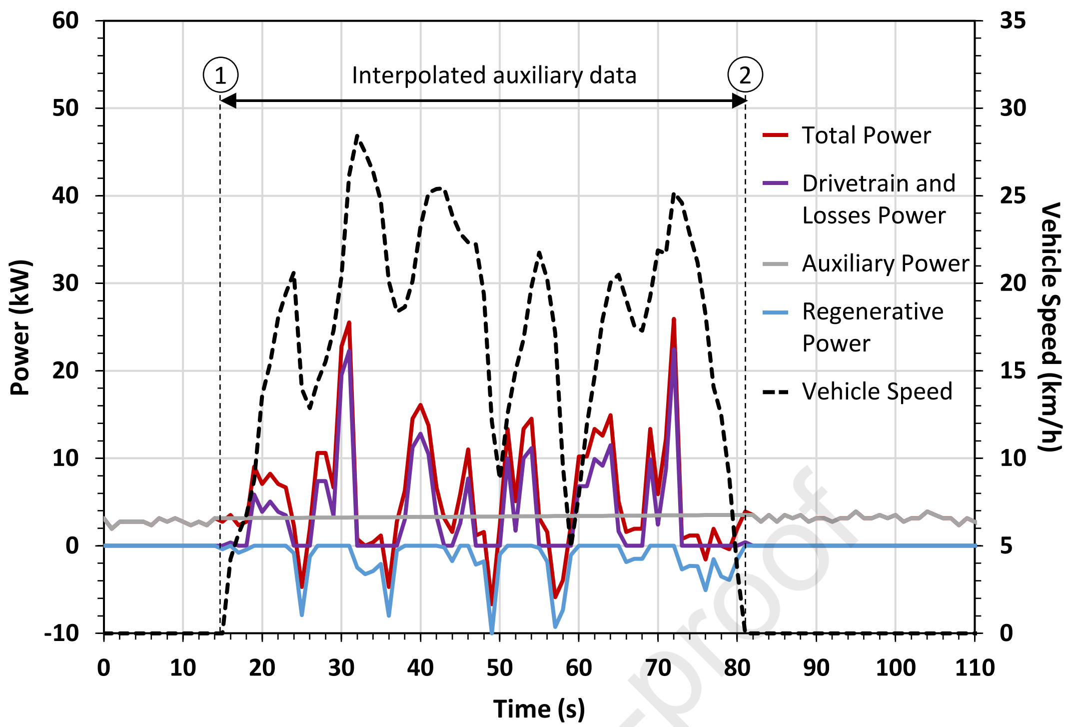



Figure 1. Graphical schematics of auxiliary power determination for scheduled and unscheduled trips.

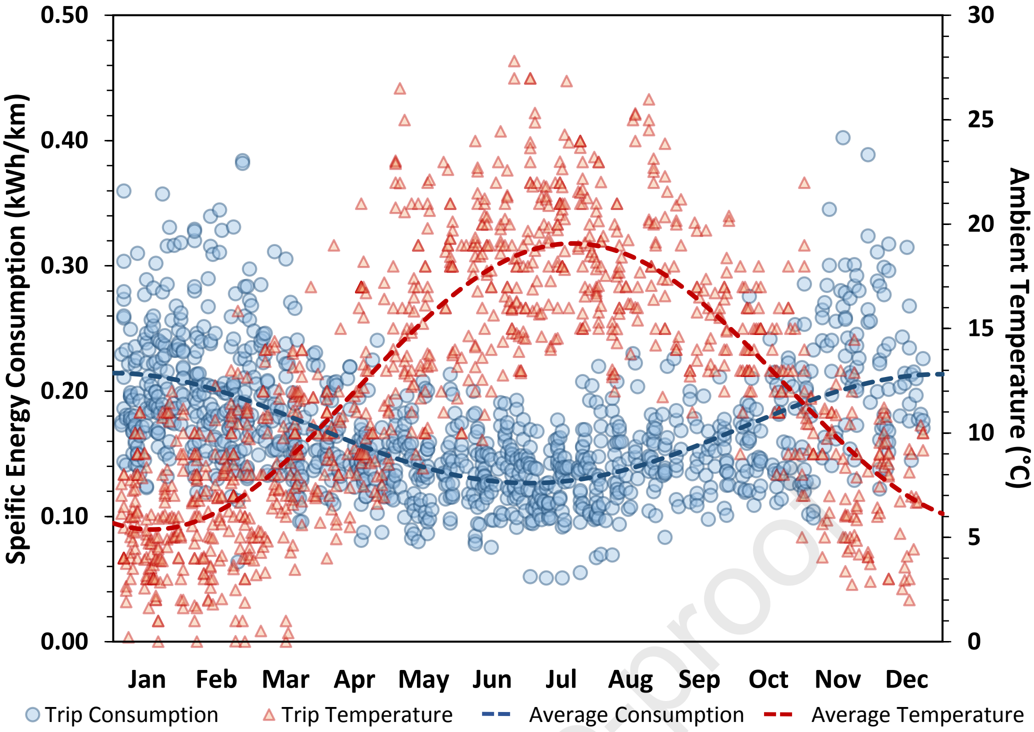
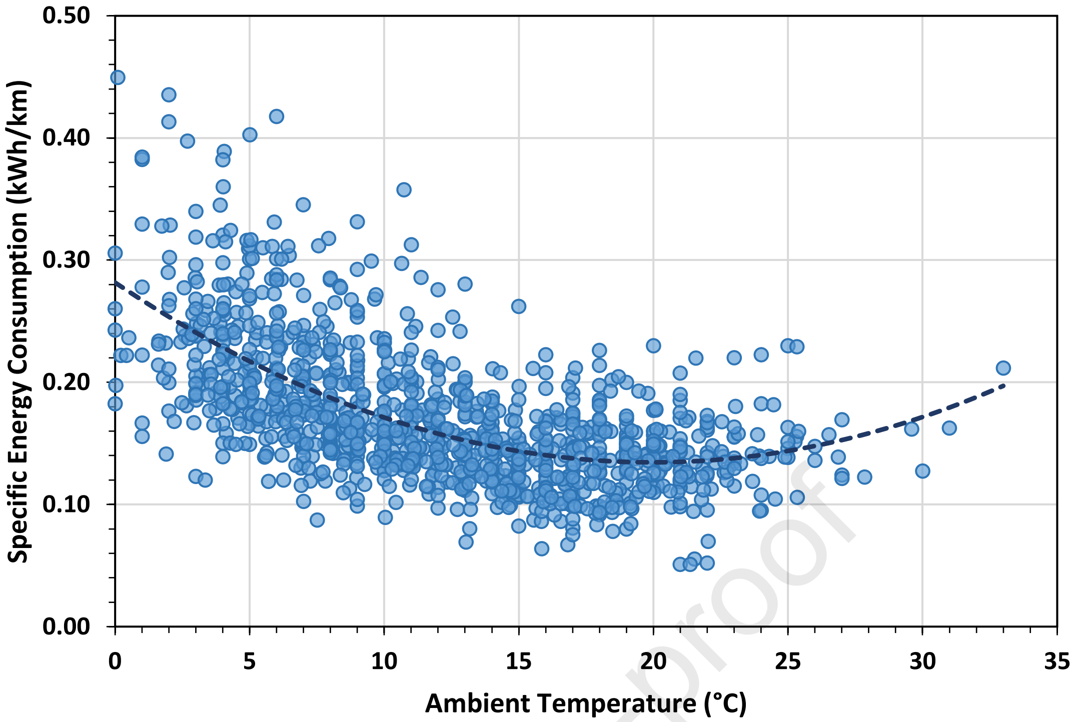



Figure 2. Monthly change in specific energy consumption and ambient temperature.

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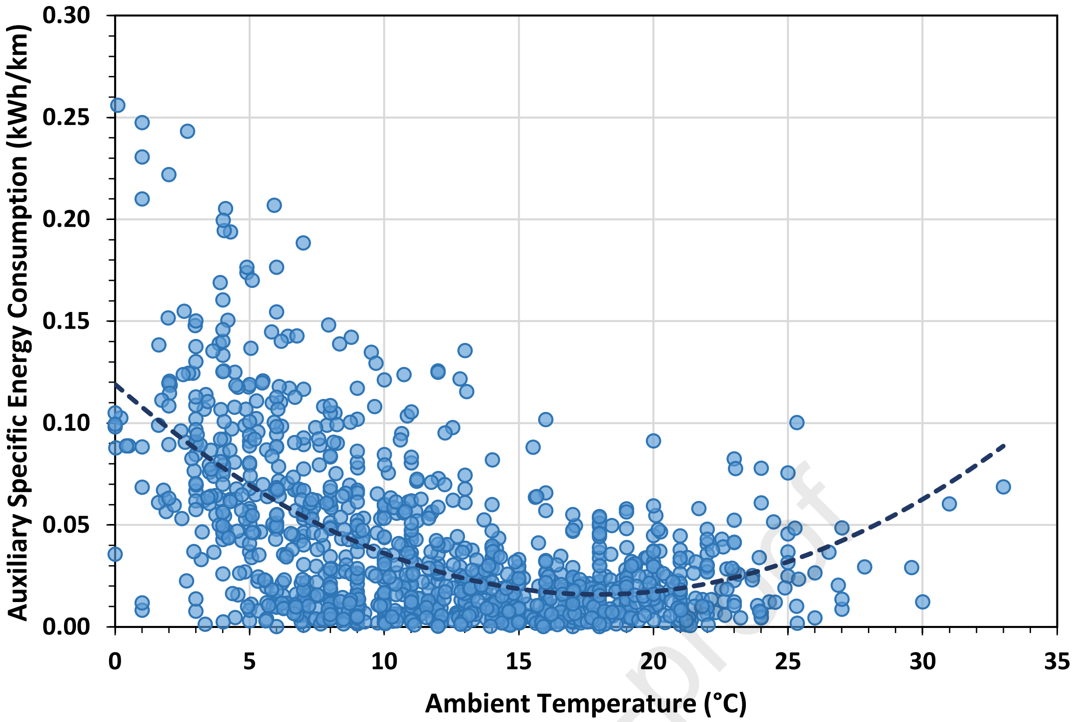


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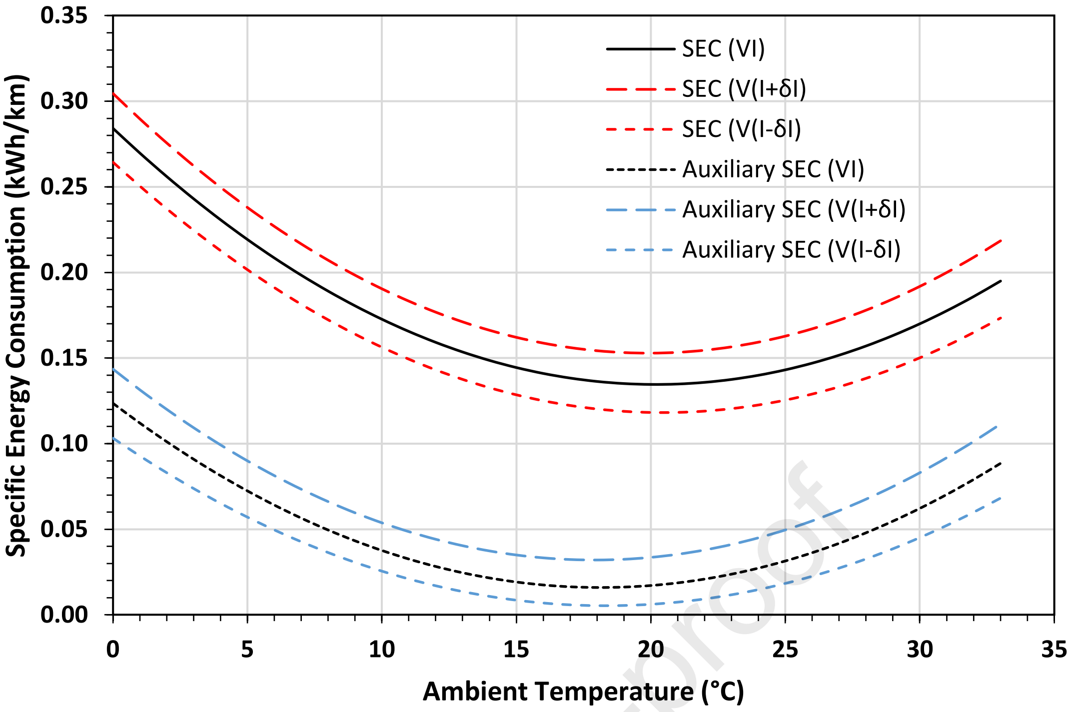


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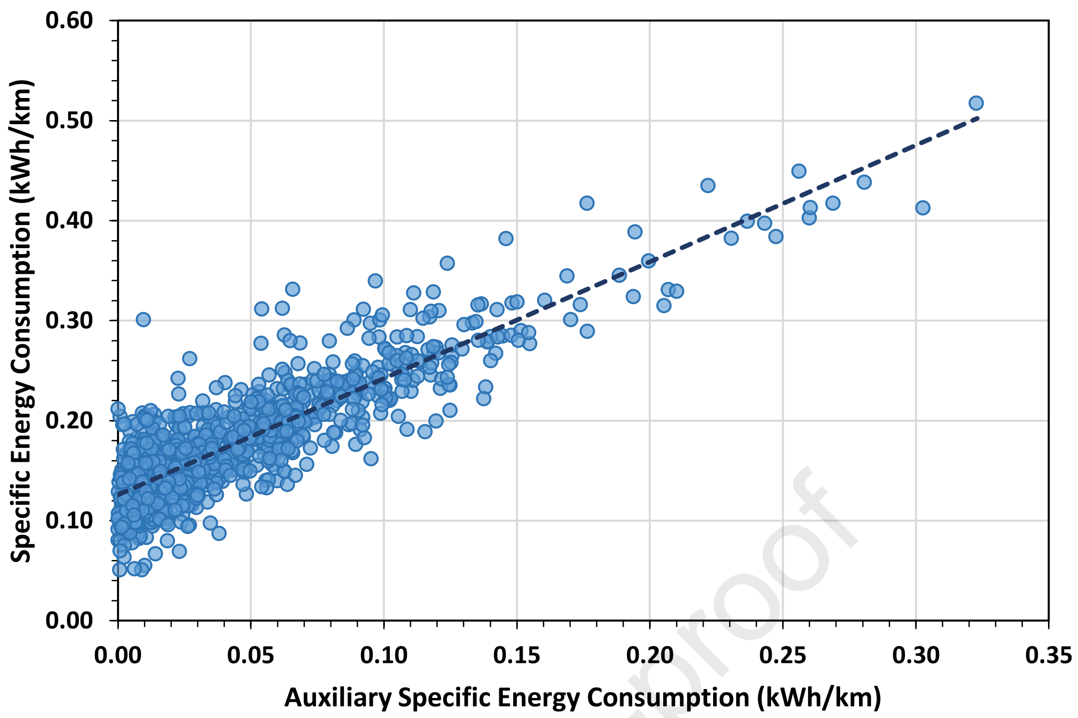


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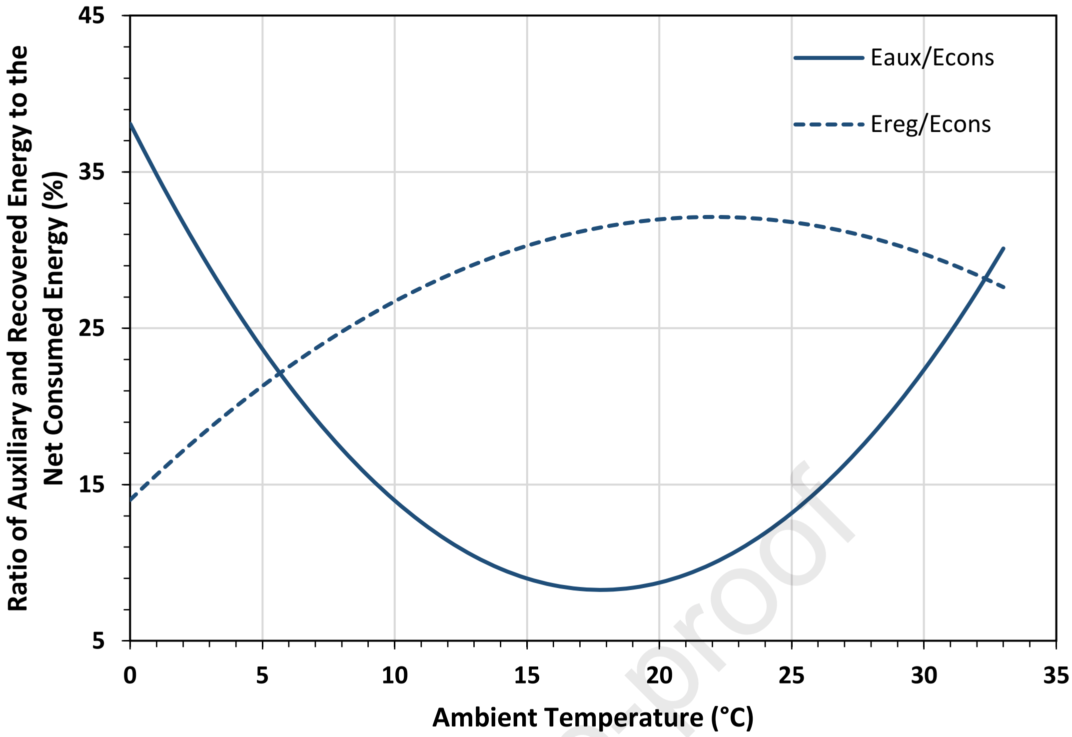


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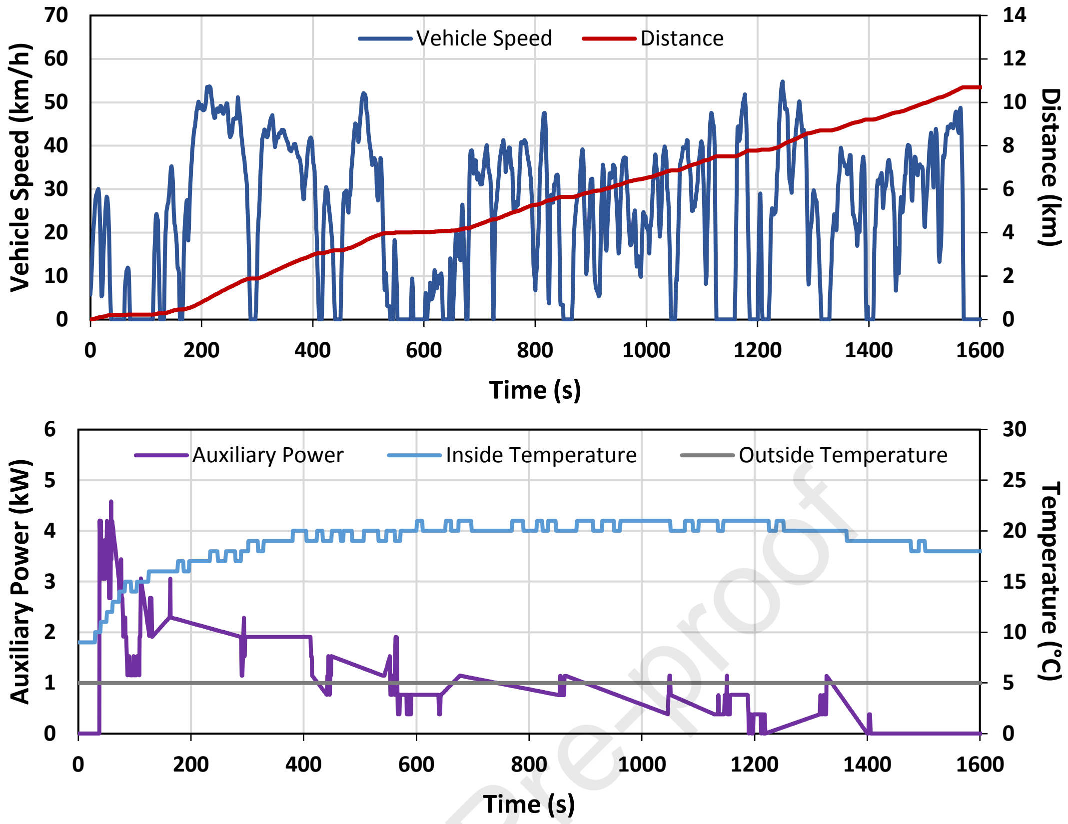


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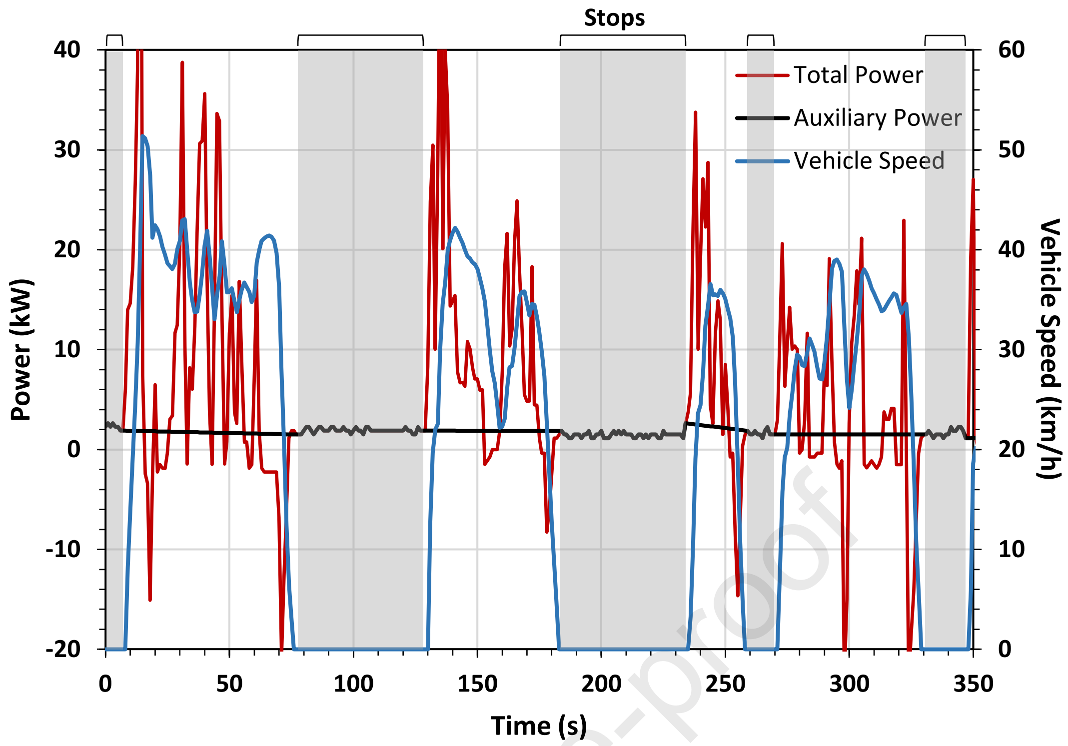


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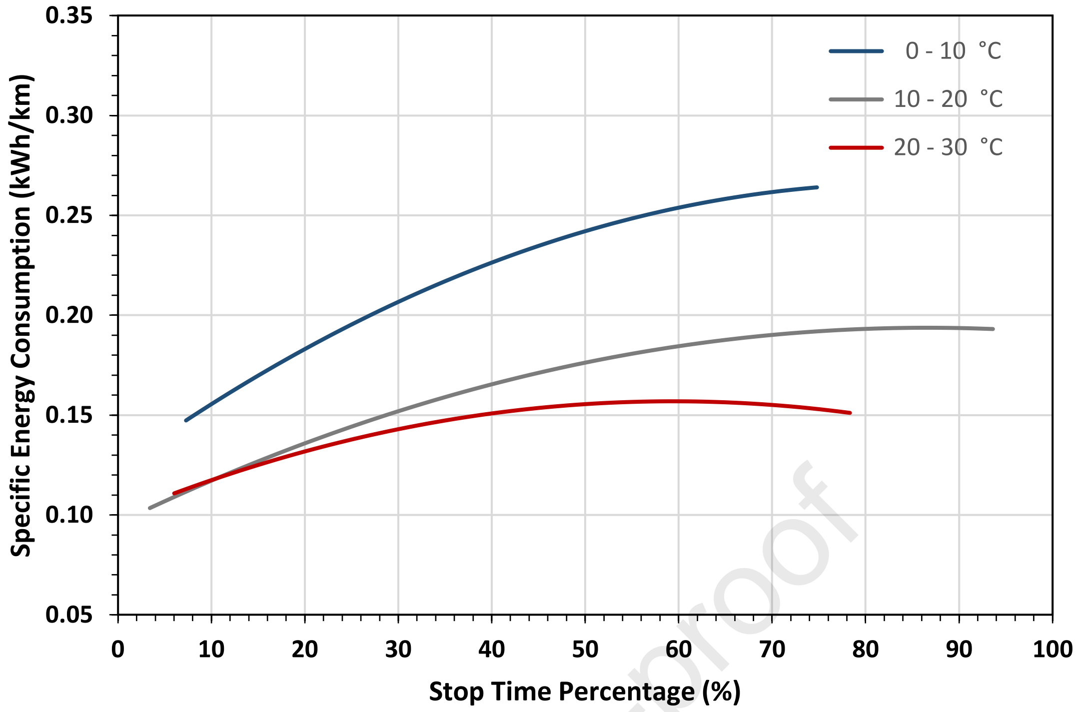


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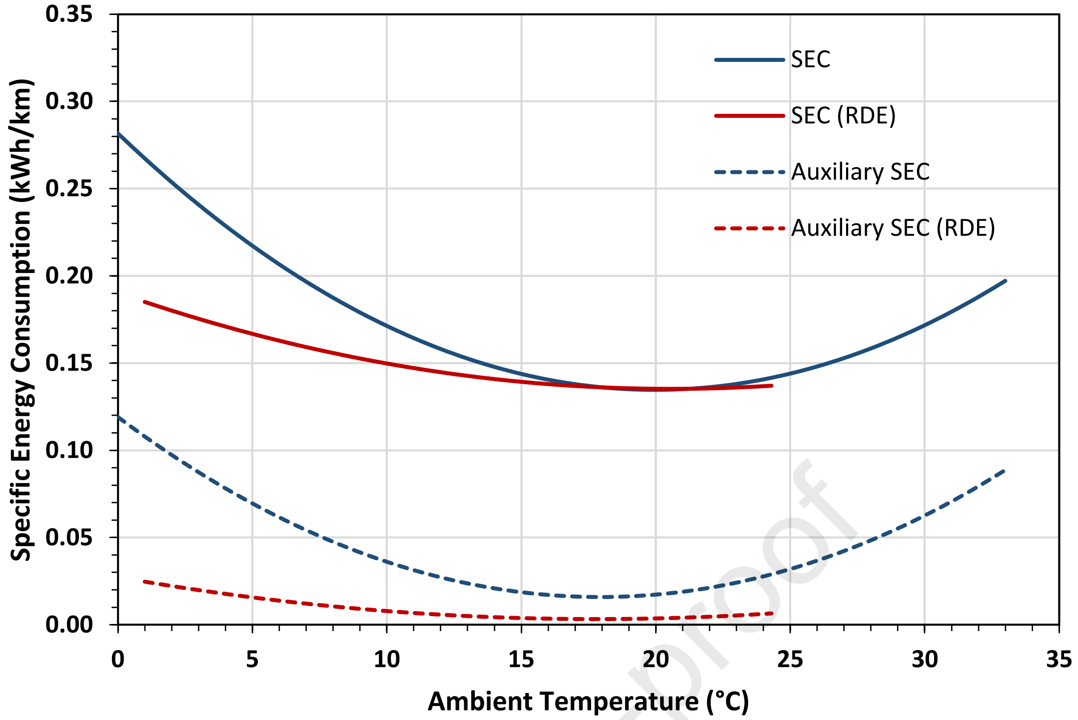


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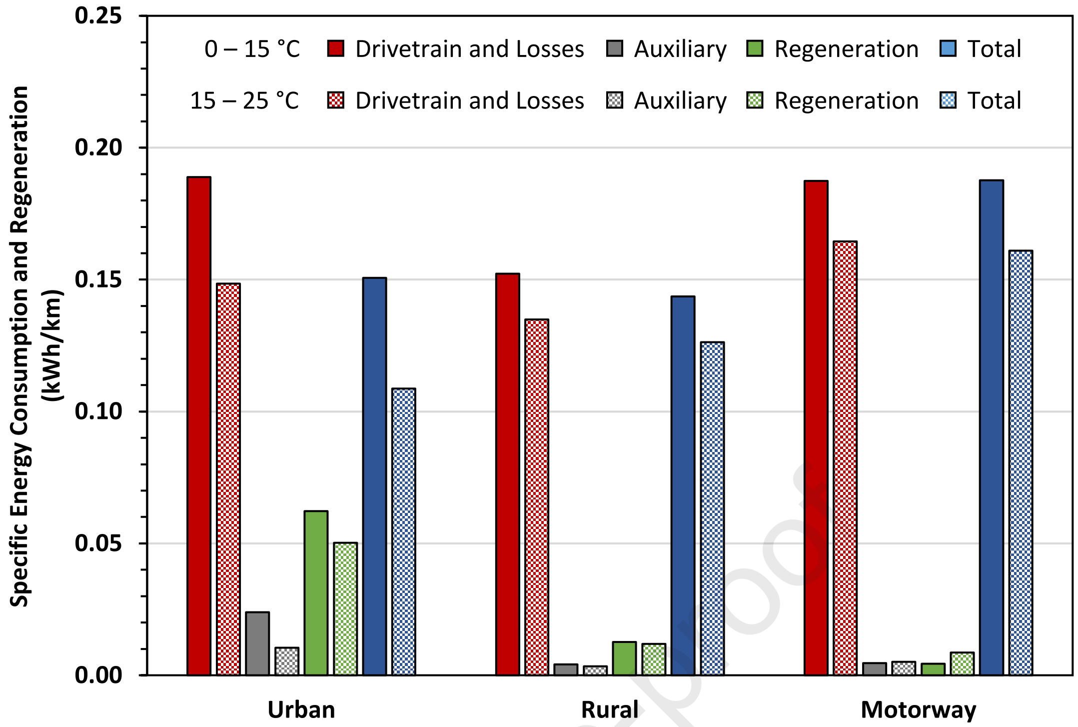


Figure 12. Breakdown of specific energy consumption and regeneration in urban, rural and motorway operation of RDE sections at cold and moderate temperature ranges.

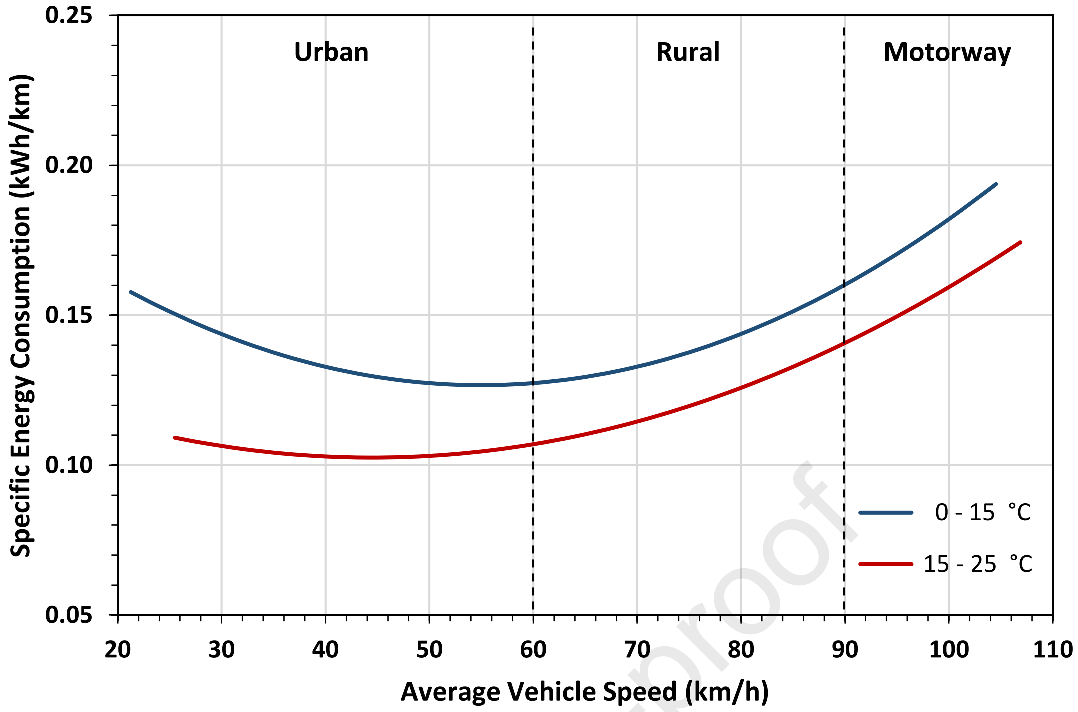


Figure 13. Variation of specific energy consumption with average vehicle speed at cold and moderate temperature ranges in urban, rural and motorway operation of RDE sections.

HIGHLIGHTS

- The ambient conditions significantly impact energy consumption of electric vehicle
- A decrease in ambient temperature leads to an increase in energy consumption
- Changes in energy consumption with temperature are related to use of auxiliaries
- Short-distance trip and low ambient temperature produce higher energy consumption
- A drop of up to 28% in vehicle range can be expected from summer to winter months

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: